Infrared Stud es of Galaxies from Space

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Abstract. The Kuiper Airborne Observatory has been a powerful instrument for the study of nearby galaxies, and SOFIA could probe still further into the local Universe. However, a comprehensive program of extragalactic exploration in the infrared - and in particular a study of galaxies at cosmological redshifts - requires the high sensitivity and complete wavelength coverage which is achievable only with a cryogenic telescope in space. This program was begun by IRAS and will be continued by the upcoming ISO (Infrared Space Observatory), WIRE (Wide field Infrared Explorer) and SIRTF (Space Infrared Telescope Facility) missions. This paper previews a set of extragalactic investigations which could be carried out by these missions.

1. Overview

Future infrared space missions can make major steps in extragalactic exploration from $z \sim 0.5$ to $z > 5$ - beyond the most distant quasars currently known. Over this redshift range one can study not only the properties - luminosity, mass, excitation conditions, etc. - of individual objects but also the evolution of classes of objects ranging from normal galaxies to the hyperluminous systems recently discovered in the IRAS data base. Here we discuss several scientific investigations which can produce such major steps. These investigations have been proposed for three upcoming infrared space missions - the European Space Agency's Infrared Space Observatory (ISO) mission (Kessler 1993) - now on schedule for launch in the Fall of 1995; the Wide Field Infrared Explorer (WIRE), which is being considered for development phase funding in NASA's Small Explorer program (Schember and Hacking 1993) and the Space Infrared Telescope Facility (SIRTF), which is in the final definition phase as NASA's observatory-class mission for infrared astronomy (Werner and Simmons 1994). Although these missions differ in scope, instrumentation, and orbit, they have in common the use of cooled optics to exploit the low background of space.

2. The Scientific Investigations

2.1. Near/mid-IR surveys for L^* galaxies to $z > 3$

Measurements of starlight from stars in distant L^* galaxies probe the formation and early evolution of the galaxies and trace the distribution of luminous matter

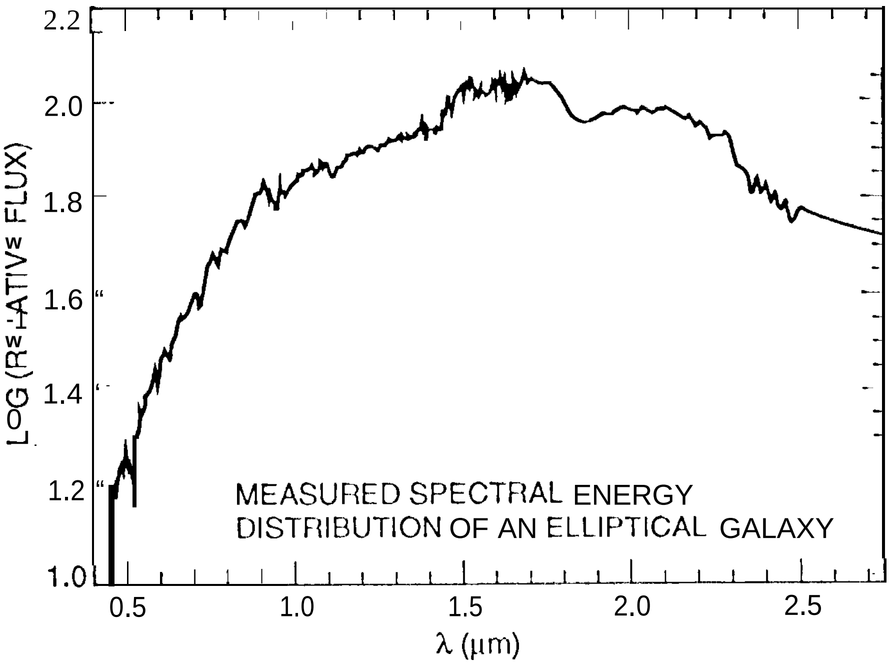

Figure 1. The rest frame visible-near IR energy distribution of an elliptical galaxy, showing the H^- emission feature at $1.6\mu m$ and the CO bandhead at $2.3\mu m$. Data provided by M. Rieke (private communication).

in the early Universe. observations of nearby galaxies between 1 and $2.5\mu m$ (Figure 1) reveal several spectral features - the $2.3\mu m$ CO bandhead and the $1.6\mu m$ emission peak due to the minimum in H^- opacity - which are present because most of the near IR radiation from a galaxy a rises from cool stars which have those features in their spectra. These features are thus relatively immune to changes in star formation rate and dust content, and are expected to appear shortly after a galaxy' forms and to persist throughout its lifetime (see e.g. Franceschini *et al.* 1991).

As an energy distribution such as that shown in Figure 1 is redshifted to longer wavelengths, the measured colors of a galaxy vary in a predictable fashion as the spectral features move through the measurement passbands (See e.g. Figure 3 of Eisenhardt and Lebofsky 1987). This variation allows the use of the observed IR colors to determine a photometric redshift. This can be done more reliably using rest frame near IR starlight than from observations at visible or ultraviolet wavelengths, which are influenced more strongly by extinction or by the presence of a small number of hot stars. For similar reasons, selection in the rest frame near IR provides a more uniform sample of galaxies above a given stellar mass than do rest frame optical or UV samples.

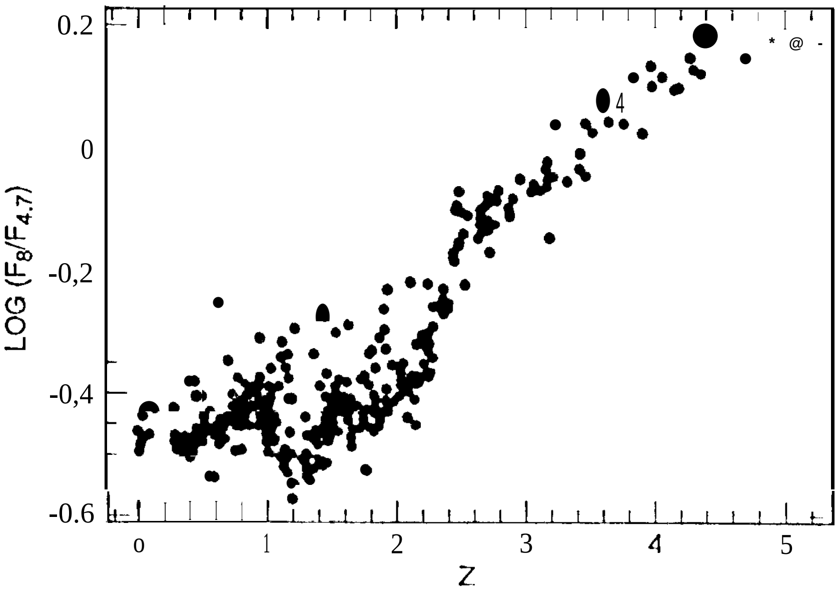

Figure 2. Relationship between 8/4.7μm flux ratio and galaxy redshift, as determined from the simulations of Wright *et al.* (1991).

An experiment based on this principle has been simulated by Wright, Eisenhardt, and Fazio (1994), using instrumental parameters appropriate for SIRTF, which will carry InSb and Si:As arrays with imaging fields of view 5x5 arcmin in extent. They assume a galaxy population normalized to current epoch observations and extending back to z=10 with luminosity and color evolution given by Bruzual (1983) models. A simulation was made of a single 5x5' field of view at 3,4.7, 6.2, and 8μm, with a total integration time of 1.6 days. The image quality and detector performance assumed were consistent with what is expected for S11{,'1'1", and the simulated data were anlayzed with standard image processing techniques. Approximately 350 galaxies were detected, including virtually all those in the simulation more massive than M^* and with z < 5. By comparing the "observed" colors of the detected galaxies in the simulated images wit]) their known redshifts, it was possible to demonstrate the usefulness of these colors as redshift indicators.

In Figure 2, for example, we show the 8.0/4.7μm flux ratio vs. redshift for this sample of galaxies. Although this ratio is relatively independent of z for z < 2, it varies systematically with z for larger redshifts, increasing by about a factor of 4 between $z \sim 2$ and $z \sim 5$. Analogous results are obtained from the other flux ratios determined in the simulation. This SI1OIVS not only that a mission such as SIRTF can detect normal galaxies at cosmological redshifts, but also that multiband imaging (lilts can be used to estimate the galaxy redshifts and thus to explore a series of problems ranging from the geometry of space-time and the presence of large scale structure in the early Universe to the evolution of the stellar populations in galaxies.

2.2. Evolution of the Starburst Galaxy Population

Future studies of galaxies at wavelengths of 10μm and beyond will be heavily basal on the results from IRAS, which inaugurated the infrared exploration of the extragalactic sky. Indeed IRAS is a "gift that keeps on giving", because the newest catalogs - the Faint Source Survey and the Faint Source Data Base - reduce the 60μm detection limit from the 560 mJy of the Point Source Catalog to about 200 mJy. As a result, the faint source data base contains five times more high galactic latitude 60um sources (presumably almost entirely galaxies) than were contained in the original Point Source Catalog. Searches based on these new catalogs have led to the discovery of the Hyperluminous Galaxies described in section 2.4. below.

One of the major results apparent from even the earliest analyses of the Point Source Catalog is that interacting galaxies are brighter at IR wavelengths than are their non-interacting cousins (Bushouse, Lamb, and Werner 1988). The IR luminosities of these otherwise fairly ordinary galaxies range up to $10^{11} L_\odot$. Based, for example, on visible wavelength spectroscopy, it has been established that the extra IR luminosity is traceable to bursts of star formation triggered by the galaxy-galaxy interactions. This scenario can be tested by tracing the co-moving density of these starburst galaxies as a function of redshift. At earlier epochs, when the galaxies were closer together, the higher frequency of interaction ought to have produced a larger fraction of IR-luminous systems. In addition, comparison of the evolution of the infrared galaxy population with that, which has been determined for quasars can test the conjecture that extremely close and violent interactions - those which lead to IR luminosities in excess of $10^{12} L_\odot$ - trigger the formation of quasars.

The WIRE mission is designed specifically to test explore these ideas by determining the evolution of the starburst galaxy population out to $z \sim 0.5$. WIRE will carry a 30-cm diameter telescope feeding two 128 $\times$ 128 Si:As arrays, which view the same $\sim 32 \times 32$ arcmin field of view simultaneously at 12 and 25μm through the use of a dichroic. The telescope and detectors will be cooled by solid hydrogen, leading to a lightweight system which can be inserted into low earth orbit by a Pegasus launch vehicle and still achieve a 4 month lifetime. WIRE's principal scientific program will be to survey 20 square degrees to the confusion limit at 25μm (approximately 1 mJy 1σ) and detect 20,000 starburst galaxies with a median redshift of ~ 0.5. Addition of the companion 12μm survey allow's - statistically - sorting in redshift and luminosity because the 25μm/12μm flus ratio increases with increasing overall luminosity. Comparing the number counts vs. flux will distinguish among various models for the evolution of this population, as shown in Hacking and Soifer (1991) and Schember and Hacking (1993), and the WIRE data base will be an invaluable source of targets for the diagnostic investigations described below.

2.3. Energy Generation in infrared Luminous Galaxies

The luminosity of IR-luminous galaxies correlates positively with the infrared-to-visual luminosity ratio. Many of the Ultraluminous Galaxies (ULGs) - those with IR luminosities in excess of $10^{12} L_\odot$) emit upwards of 99% of that luminosity in the IR (Soifer 1993). At this luminosity level, either extreme starburst activity or an embedded quasar might be the fundamental energy source, and differential variations of the gas phase neon abundances within a so urce. Of [Particular importance in the present context is the fact that the lines lie close together in wavelength and in a spectral interval where extinction by dust is weak and spectrally smooth. Thus the line ratios are only imperceptibly influenced by differential exctinction even if the region is observed through 100 magnitudes of overlying visual extinction.

Because the NeIII (15.6μm) and NeV (14.3μm) wavelengths are totally blocked by CO_2 in the Earth's atmosphere, application of this diagnostic to nearby galaxies - even to very bright ones - requires observations from space. Observations of this type on known in frared galaxies will be carried out with the Short Wavelength Spectrometer on ISO. Similar investigations on more distant, fainter galaxies will be carried out by SIRTF, using targets selected from the WIRE survey and from SIRTF's own deep surveys. SIRTF's spectrometers will be instrumented with 12 8 $\times$ 128 Si:As and Si:Sb arrays which will be sensitive at least to 40μm. Use Of these arrays in echelle spect rographs which cover several spectral 01'(1('1'S simultaneously will provide simultaneous observation - till'o[l~ll the same entrance slit - of all three lines in galaxies 0111 to redshifts $z > 1.5$.

2.4. The Most Luminous Galaxies

Exploration of the IRAS Faint Source Survey and Data Base has led to the discovery of the most luminous known galaxies. The most notorious (and lumminous) of these objec ts, FSC10214+4724 (R owan-Rob inson *et al.* 1991) appeared in the Faint Source Catalog as a (if)// Ill only source with 60μm flux = 190mJy. Follow up observatio ns led to the identification of this 60μm source with an optically faint galaxy at redshift $z = 2.286$, giving FSC10214 a luminosity of $\sim 5 \times 10^{14} L_{\odot}$. Two other galaxies having luminosities within an order of magnitude of F SC10214 have also be en identified - PSC09 104+4 109 (Kleinm a n n *et al.* 1988) and FSC15307+3252 (Cutri *et al.* 1994) - and the latter authors introduced the label Hyperluminous Galaxies (HLGs) to identify this Class of objects. The nature Of the processes which produce these gargantuan luminosities is unclear. At $10^{14} L_{\odot}$, agaaxy with 10^{11} $M_{\odot}$ co nsum es its nuclear fuel in $< 10^8$ yrs, which has led to the suggestion that objects of this type are protogalaxies undergoing the initial burst of still" formation which is thought to accompany their initial collapse. This star formation hypothesis is consistent with the enorm ous qua ni tity of interstellar gas and dust discovered in FSC10214. On the other hand, the fact that the luminosities of these objects lie in a range previously occupied only by the most luminous quasa rs suggests that a hidden quasar may be the energy source (see e.g. Elston *et al.* 1994).

SIRTF can further our understanding of this intriguing phenomenon by detailed studies of individual objects - for example using the spectroscopic probes mentioned previously - and by additi onal surveys aim ed at uncovering additional examples. Sill'1'I''si]l]2lgil]g arrays will survey large areas of sky to 60μm flux levels far below the IRAS FSC limit. For example, SIRTF can survey about 50 square degrees to a limiting 60μm flux of 1mJy (5σ) in about 100 days. This survey would include about 10^5 gala xies. Sorting through this cosmic haystack in search of the 3000 ULGs and 100 HL Gs it is expected to include (the numbers will be greater if strong cosmic evolution occurs) poses an inte resting challenge. One possible approach to this search is to use the fact tha t the sha pe of the rest

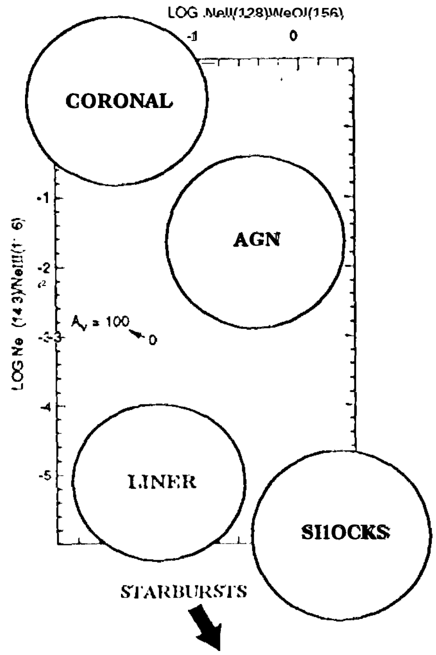

Figure 3. The regions in the (NeII/hTclll, NeV/NeIII) infrared line ratio plane corresponding to different possible ionization and energy sources are shown.

either possibility would have interesting consequences. Because the observed IR radiation is thermal emission from dust which has been heated by the primary power sources, continuum IR observations alone cannot distinguish among these and other possibilities.

For less heavily dust-enshrouded sources, optical emission line spectroscopy provides a means of distinguishing between thermal and non-thermal ionizing spectra, which would be associated with starburst or quasar energy sources, respectively. For sources which emit > 99% of their total luminosity in the IR, however, any optical emission produced in the immediate vicinity of the central energy sources is likely to be very highly extincted, and the optical emission observed from these galaxies may arise in their less interesting outer regions. Infrared emission lines can emerge from the enshrouding dust, however, so that, IR spectroscopy is potentially capable of providing the diagnostic information needed to identify tile character of the energy sources.

Voit (1992) has drawn attention to a particular set of emission lines which are uniquely Usr'fill for this type of diagnostic spectroscopy. These are lines of three different ionization states of neon: NeII at 12.8μm, NeIII at 15.6μm, and NeV at 14.3μm. The ionization energies to produce these three ions are, respectively, 22, 63, and 97 eV. Thus, as shown in Figure 3, the relative intensities of these three emission lines are highly indicative of the character of the ionizing source. This triad of neon lines has other important characteristics: since they arise from different ionization states of an element which is particularly unlikely to be depleted onto interstellar grains, their ratios should not be influenced by

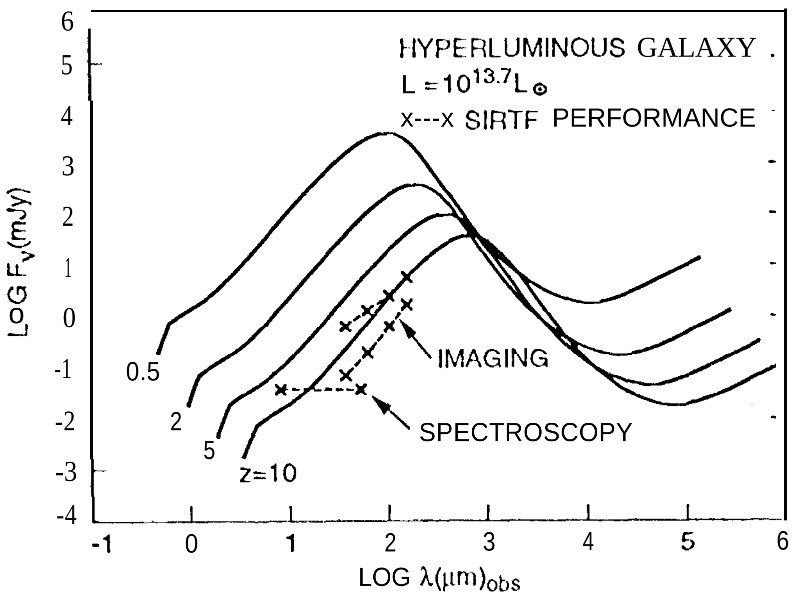

Figure 4. The capability of S1l{'l'l' for imaging and spect roscopy of Hyperluminous Galaxies as a function of redshift are shown. The imaging perfo rmance is given as 1σ uncertainty in 10 and 1000" seconds of observation], while for spectroscopy, we show the 1σ uncertainty in 3600 seconds.

frame energy distribution of the three 1 Il ,G's mentioned above is the same to better than a factor of two, as shown in Figure .3 of Cutri *et al.* (1 994). The similarities of these energy distributions allow's one to concoct a color-based criterion to select candidate ULG's from the survey data base. SIRTF's instrumentation is being designed to permit imaging at several wavelengths simultaneously. In addition, SIRTF's surveys would be coordinated with other large scale surveys, such as WIRE and the Sloan Digital Sky Survey, to create a multispectral data base which would facilitate the selection process.

Figure 4 Snows that Sill'l'J' can obtain high quality imaging and follow up spectral data on ultraluminous objects as distant as z > .5, beyond the most distant quasars currently identified. This program would define the luminosity function of $L > 10^{12} L_\odot$ systems from $z = 0$ to $z > 2$, determine the energy generation processes which power these tremendous luminosities - and delineate their variation (if any) with redshift. For faint dist ant objects with high infrared-to-visual ratios, SIRTF's spectroscopy may be the only means of determining redshifts. This may be possible even for HLGs with $z \sim 10$ (assuming that there are any), for which the 3.28μm "PAH" emission feature is shifted to beyond 35μm. SIRTF surveys would probe the evolutio nary connection between ultraluminous objects and quasars and explore the possibility that these objects are in fact protogalaxies. Finally, SIRTF can go beyond the horizon of our present understanding and determine whether ULG's exist, at $z > 5$ and whether there are objects with properties ev en more ext reme than those identified to date.

3. Summary and Conclusions

Just as the success of the I{ AC) has paved the way for larger airborne telescopes such as SOFIA, the success of IRAS and COBE has set the stage for the next steps in infrared astronomy from space. This paper has highlighted a few areas of extragalactic astronomy in which future cooled space telescopes - particularly when instrumented with large format IR detector arrays - can make major contributions. The scientific prospects for such facilities arc virtually unlimited, and wc hope that the examples put forward here will stimulate even more exciting ideas in the readers' minds.

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